EXPERIMENTS ON COLOR SATURATION[1]

By L. R. Geissler

The following experiments are a part of a more elaborate study of color saturation which has been interrupted for the present, but may be resumed later. Nevertheless, the results thus far obtained are presented in their unfinished form, since they may be of use to others interested in the problems of color-vision.

The only experimental work on color saturation which the author has found in the psychological literature dates back to the sixties of the past century. In 1865 Aubert published[2] some measurements on the liminal sensitivity to color saturation. He determined the smallest sector of color that would appear as a just noticeably colored ring on a rotating white disc and found it to be 2 to 3 degrees, while on black and gray discs even smaller sectors were recognized. He also made some experiments on the differential limen of color sensitivity; and he found that on a black background the stimulus-increment for orange must be 0.95 per cent, for blue 1.54 per cent, and for red 1.67 per cent, in order to produce a just noticeable increase in saturation. Aubert used the Masson-Maxwell disc, and observed under ordinary daylight illumination. It is not stated whether he employed any observer besides himself; but in a later summary of his results[3] he remarks that they were confirmed by J. J. Müller,[4] who does not give any account of his experiments, and by M. Woinow.[5]

Our problem was to determine whether the number and sizes of colored stimulus-increments corresponding to just noticeable saturation differences would lend themselves to a measure of saturation. We began our attack upon this problem from the two extremes,—by gradually reducing a maximally saturated pigment-color, and by introducing more

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[1] From the Physical Laboratory of the National Electric Lamp Association, Cleveland, Ohio.

[2] H. Aubert, *Physiologie der Netzhaut,* Breslau, 1865, 138-150.

[3] H. Aubert, *Grundzüge der physiologischen Optik,* Leipzig, 1876, 531-532.

[4] J. J. Müller, Zur Theorie der Farben, *Graefe's Archiv f. Ophthalmologie,* xv., *Abth.* 2, 1869, 243.

[5] M. Woinow, Zur Frage über die Intensität der Farben-Empfindung, *Graefe's Archiv f. Ophthalmologie,* xvi., 1870, 251-264, esp. p. 256.

and more color into a colorless stimulus. Both groups of experiments were performed under an artificial daylight illumination of constant intensity and constant spectral composition. The rotating double color-disc was mounted on a Lummer-Brodhun color-mixer with peripheral attachment and viewed against a perfectly neutral grey background. The stimulus was exposed for three seconds at a time and the interval between two exposures was always made long enough for after-images to disappear. Our colored stimuli were Zimmermann papers of the following hues: red (d), yellow (h), green (l), and blue (n), mixed with Zimmermann greys of corresponding degrees of brightness. The colors were equated with the greys by the method of flicker-photometry, the voltage readings of a Weston electric speedometer being taken as an indirect indicator of the speed of the color-mixer. The grey which at lowest voltage, and hence at slowest speed, mixed with a color without flicker, as determined by several observers, was regarded as being of the same brightness as the color. The equations thus found agreed in the main with the introspectively estimated equations made by a number of observers well trained in photometric work, as the following Table shows, in which the small letters indicate the greys as taken from the Zimmermann set of thirty-five greys.

Equation of Color and Greys

Obs.	*Yellow*	*Green*	*Red*	*Blue*
	Natural Daylight			
A	a-b	e	k	r
B	b	f	m	p
C	b	d	n	q
	Artificial Daylight			
A	a-b	e-f	h	s
B	c	d	l	p
C	b	e	m	q
	Flicker-Photometry			
	b	d	m	r

Since grey *a* is the lightest in the series, almost a white, the order of our colors according to brightness is from brightest to darkest: yellow, green, red, and blue. The difference between yellow and green is the smallest; that between green and red the largest; and that between red and blue is intermediate. The use of the peripheral attachment of the Lummer-Brodhun color-mixer makes it possible to compare a colored

ring on the outside, which is kept constant, with a colored disc on the inside, which can be varied during rotation.

In our first group of experiments we worked with red only. Two of the four observers were more or less trained in psychological experiments, namely, Miss Wilma Ball (B), of Cleveland, who kindly volunteered her services in the interest of psychology, and the writer (G). The other two were Messrs. G. Cadish (C) and L. Krill (K), both employed in the Laboratory and familiar with photometric work and observations.

Employing the 'method of limits' we began with maximal saturation, that is, 360 degrees of red, both outside and inside, and gradually added small amounts of grey (m) to the inside, until it looked just barely less saturated than the outside. Reversing the procedure, the inside was made definitely less saturated, and then step by step more red was added until it looked like the outside. At least six such pairs of series were taken, and in half of them the judgments 'more saturated,' 'less saturated,' 'equal,' or 'doubtful' referred to the outside as compared to the inside, while in the other half the reverse was the case. The average amount of grey thus found to be necessary in order to make the inside look just less saturated than the outside was then introduced in the outside, so that now the inside had to be changed still more, before it again seemed to be just less saturated. Then the outside was again reduced by the corresponding amount of grey; and similar series were taken to determine the next step. This procedure was continued until the outside had been reduced from 360 degrees color to about 300 degrees color *plus* about 60 degrees grey. It was intended to continue the method for red down to the color-limen, and then to repeat it with several other colors, at least at certain stages between 360 degrees and 0 degrees; but unavoidable external circumstances prevented this. It was possible to carry on the experiments for red with two observers, B and G, only in the regions of 240-222 degrees and 120-110 degrees of red *plus* the corresponding amount of grey. With C and K a few unsystematic observations were made at the same places, giving similar results.

The detailed results are presented in the following Table, in which the stimulus-increments are given for each observer. The figures in the odd columns indicate the size of the red sector in the outside ring at the stage corresponding to the preceding and succeeding steps. Observer C, for example, distinguished 360° of red in the outside from 350° red *plus*

10° grey in the inside, and the latter amount of saturation in the outside from 346.5° red *plus* 13.5° grey; or in other words, the third degree of saturation was produced by adding 3.5° of grey to the previous amount of grey. In calculating the Av. and MV. for C and K the last two approximate values were included.

B	C	G	K
360.0°	360.0°	360.0°	360.0°
13.0	10.0	10.0	10.0
9.0		6.5	8.0
7.0	350.0° 3.5	7.5	5.0
6.0	3.5	7.0	5.0
	5.0	5.5	4.5
325.5° 4.0	4.0		6.5
3.5	3.0	323.5° 3.5	5.0
4.5	4.5	3.0	
4.0	3.5	3.5	316.0°
5.0	3.0	3.0	
	4.0	4.0	
302.0°	4.5	4.0	
	311.5°	302.5°	
240.0°	240.0°	240.0°	240.0°
3.0		3.5	
4.5	about 4.0	5.0	about 4.5
5.0		3.0	
4.0		3.0	
223.5°		225.5°	
120.0°	120.0°	120.0°	120.0°
3.5		2.5	
3.0	about 3.5	3.5	about 4.0
4.0		3.5	
109.5°		110.5°	
Average and Mean Variation of last 12 steps 4.0 ± 0.5	Average and Mean Variation of last 12 steps 3.85 ± 0.5	Average and Mean Variation of last 13 steps 3.5 ± 0.42	Average and Mean Variation of last 7 steps 4.9 ± 0.51
0.0° 1.25	0.0° 0.81	0.0° 1.56	0.0° 1.31

The Table shows at a glance that, so far as this particular pigment red is concerned, the stimulus-increments corresponding to just noticeable saturation-differences are approximately constant at such different stages as 325° red *plus* 35° grey, 230° red *plus* 130° grey, and 110° red *plus* 250° grey. It seems fair to assume that the increment-values would have remained constant at the intervening stages, and perhaps also at a stage not far removed from the absolute color-limen, which is given in the last horizontal row of the Table. If this result is verified by later experiments, it will allow us to estimate the approximate number of least perceptible differences in the saturation of our pigment-red, and to say that it is close to one hundred. We have a few systematic data for observer K on green mixed with grey *d*, which is thus a good deal lighter and, at the same time, less saturated than red. It is significant that the first four stimulus-increments required to reduce green by smallest possible changes in saturation are considerably higher than those for red, namely, 17, 14, 9, and 12, as compared with the corresponding values for red, which for K were 10, 8, 5, and 5. The difference seems to indicate that the original saturation and brightness of the color measured have some very definite influence upon the size of the just noticeable saturation-differences. If these results could be confirmed and extended to other colors, they would simplify the problem of measuring saturation far beyond our expectation; but at present we must refrain from basing any speculative conclusions upon them.

Our second group of experiments was performed under the same external conditions and by the same method. In addition to red, the colors yellow, green, and blue were used; and besides binocular vision we also made determinations for each eye separately. There were altogether nine observers: C, G, and K of the previous group, Miss M. Majerus (M), Messrs. C. F. Lorenz, Ph.D. (Lo), M. Luckiesh (Lu), A. G. Worthing, Ph.D. (W), of the Physical Laboratory, and Mrs. L. R. Geissler (SG) and Mr. F. Aeberli, M. D. (A), of Cleveland, O.[6] The observers thus represent various degrees of practice, while their age ranges between eighteen and thirty-eight. It was thought advisable to test a fairly large number of observers, in order to eliminate individual peculiarities of color-vision, and also to get a comparison of the sexes. Our results seem to justify the precaution. The monocular data

[6] Several other observers began the experiments, but for various reasons could not continue. The writer takes this opportunity to thank each and all of them for their willing co-operation.

were obtained by placing a ground glass before the unused eye.

The detailed results are presented in the following Table. Each individual value for both eyes, for the right eye alone, and for the left eye alone is the resultant of eight series of determinations, while the figures of the rows headed 'totals' are the averages of the values for both eyes, and the right and left eye. The arrows indicate the direction from smaller to larger differences of the totals, and are inserted to facilitate the grouping of the observers. If we consider first the combined results of all observers,—in other words, the averages of the totals,—we find that the smallest increment necessary to distinguish between color and no color is required for our red, varying between 0.68° and 4.06° and averaging 2.23° ± 0.85°. Then follow blue, yellow, and green and this order agrees with that according to saturation, red being the most and green the least saturated of our colors. Since our green requires a limen three times as great as that of red, it seems reasonable to assume that its saturation is only one-third as great as that of our red, and, similarly, that the saturation of our yellow is about one-half of that of our blue, that of blue about five-sixths of red, and green five-sixths of yellow. These figures agree approximately with a number of estimates of saturation made by some of our observers as well as by outsiders, even to the point of individual differences; for two of our observers, who estimated the blue to be more saturated than the red, also gave a smaller limen for blue than for red. We do not wish to lay emphasis upon these quantitative relations of color saturation, because a larger number of colors should be investigated before any general conclusions can be derived from the experiments; but we believe that our method will lead to a reliable measure of saturation.

We may now consider the results of the nine individual observers. At first glance there seems to be little agreement among them; but a closer study shows that eight give a higher limen for yellow than for blue (although one of the eight shows an unappreciable difference only), seven have a higher limen for green than for yellow, and six give a smaller limen for red than for blue. The average difference between red and blue is 1.51°, between yellow and green 2.15°, and between blue and yellow 2.90°, showing that, on the whole, red and blue were more nearly equal in saturation than yellow and green, and especially than blue and yellow. The individual deviations from the general average are smallest in the case

TABLE OF ABSOLUTE LIMINAL VALUES FOR COLOR-SATURATION

Obs.	Vision	Red	Blue	Yellow	Green
	Both	.81	1.25	1.31	1.69
	Right	1.00	1.19	1.37	1.87
C	Left	.87	1.24	1.31	1.66
	Total	.90 →	1.23 →	1.33 →	1.74
			.33	.10	.41
	Both	1.31	5.28	6.62	7.37
	Right	2.06	6.50	6.87	7.88
K	Left	1.81	5.63	7.62	7.63
	Total	1.73 →	5.80 →	7.04 →	7.63
			4.07	1.24	.59
	Both	.62	3.00	5.87	10.25
	Right	.62	3.00	6.25	12.12
Lu	Left	.81	3.50	5.87	12.56
	Total	.68 →	3.17 →	6.00 →	11.64
			2.49	2.83	5.64
	Both	1.18	2.78	8.12	8.00
	Right	1.56	2.18	9.62	9.48
Lo	Left	1.75	2.56	10.75	9.12
	Total	1.50 →	2.50 →	9.50 ←	8.87
			1.00	7.00	.63
	Both	3.25	4.62	9.25	6.25
	Right	4.50	4.00	10.00	7.12
M	Left	4.43	4.25	11.00	8.32
	Total	4.06 →	4.29 →	10.08 ←	7.25
			.23	5.79	2.83
	Both	1.56	4.12	3.93	7.37
	Right	2.12	4.78	3.81	7.12
G	Left	2.56	5.02	5.09	8.12
	Total	2.08 →	4.64 ←	4.28 →	7.54
			1.39	.36	3.26
	Both	2.16	1.56	3.09	5.37
	Right	3.19	1.37	2.59	5.75
W	Left	2.87	1.12	3.12	5.63
	Total	2.74 ←	1.35 →	2.93 →	5.58
			1.39	1.58	2.65
	Both	2.81	2.12	6.62	6.87
	Right	3.56	1.69	5.25	6.75
SG	Left	2.75	1.93	6.12	6.63
	Total	3.04 ←	1.91 →	6.00 →	6.75
			1.13	4.09	.75
	Both	2.27	2.12	4.62	7.66
	Right	2.43	2.00	5.12	7.33
A	Left	2.62	2.03	5.62	8.12
	Total	2.44 ←	2.05 →	5.12 →	7.70
			.39	3.07	2.58
	Both	1.77 ±.75	2.98 ±1.24	5.99 ±1.88	6.76 ±1.55
Av. of	Right	2.36 ±.85	2.97 ±1.42	5.65 ±2.14	7.27 ±1.72
all	Left	2.27 ±.86	3.03 ±1.39	6.28 ±2.34	7.54 ±1.93
Obs.	Total	2.23 ±.85	2.99 ±1.32	5.81 ±2.11	7.19 ±1.69
			1.51	2.90	2.15

of green, where there are only two extreme values; next follows yellow, then red, and finally blue, where the mean variation amounts to .44 of the average. So far as sex is concerned, the averaged results of the two women observers

are greater in the case of three colors than the general average, and in the case of green equal to it, while the seven men average better than the total with red and yellow, equal with blue, and slightly worse with green. Age seems to have no influence upon the liminal sensitivity; and, similarly, long experience with colors and photometric work showed no effect.

It was found, again, that the binocular averages are considerably lower than the total and the monocular results. In twenty-two out of thirty-six cases the binocular averages were lower; in ten cases the right eye, and only in four cases the left eye was lowest. The right eye was slightly superior to the left with all colors but red.

Our results cannot be directly compared with those of Aubert and with the other earlier work, because of the differences in the external conditions. But we tried to determine whether natural daylight, which, of course, is several times as bright as our artificial illumination, would bring about radically different results. The two observers G and K, with whom this comparison was made, gave the following results under natural daylight: red 2.37 and 2.17, blue 1.83 and 2.96, yellow 7.84 and 6.85, and green 5.84 and 6.25; or in words, both gave a much lower limen for blue, while for G yellow and green practically changed places and for K the limen of green was lowered. Since these experiments were carried on between 11:00 A. M. and 3:30 P. M. before a brightly illuminated window facing the shining mid-day sun, the yellowish hue of the light would, by contrast, appear more saturated and therefore reduce its limen, while for G it also considerably reduced the saturation of the yellow stimulus, presumably on account of adaptation, although for K no such effect was noticeable. The striking fact is that the limen for blue in natural light was lowered.

Finally we attempted to verify some of Aubert's results by using the Masson-Maxwell disc; but instead of projecting the color on black or white, we used a grey disc of the same tint as the color, while everything else was copied from Aubert's description. K saw the innermost ring of green definitely and constantly as a faint colored ring; the next ring was seen only barely colored, and fluctuated; the third was absolutely colorless, slightly dark, and unsteady; and the other three could not be seen at all. For G, the innermost ring was clearly colored green and always visible; the next was less definitely colored but was constantly seen; the third fluctuated and was barely seen as color; the fourth was visible only during very brief intervals and showed no color, being

just slightly darker grey than its background; and the other two were entirely invisible. The six small green squares which produced these rings were 5.5 mm and the intervening spaces 10 mm, thus corresponding from periphery to center to sectors of the following angles: $3°0'$, $3°37'$, $4°27'$, $6°02'$, $8°20'$, and $14°50'$. Accordingly the limen for G was $6°02'$ and for K $8°20'$; or, in other words, these values correspond as closely as can be expected with our previous data; but they are considerably greater than Aubert's figures. The difference must therefore be due to his use of black and white backgrounds instead of backgrounds of the same tint as the color investigated. The fact that both G and K could see a colorless ring slightly darker than the background seems to indicate that our equation of tint for color and grey as determined under artificial daylight was not absolutely true for the much higher intensity of natural daylight. The difference between color and background in Aubert's experiments must have been much larger, and hence may have produced colorless rings of light or dark grey which he may have interpreted as color-values; thus he may have obtained his lower limen. It must be left to further experiments to clear up the point.

We were fortunate enough to get a few observations on the color-limen from a color-blind person, but could not make a careful analysis of his defect at the time. His results afford, however, an interesting comparison with the normal averages. He gave the lowest limen for blue as 8.25° as against 2.99°; then yellow, 18° against 5.81°; then red 37° against 2.23°; and finally green approximately 140° against 7.19°,—but even then the color was named yellow rather than green. It may be mentioned in this connection that with every observer we had recourse to preliminary series for introspective descriptions of the liminal colors, the presence of after-images, and contrast-colors in the surrounding field; but the data thus far obtained are too incomplete to be included here.